

Recent progress in radio occultation science and retrievals with a focus on climate applications

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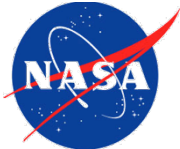
Jet Propulsion Laboratory, California Institute of Technology

CLARREO Science Definition Team Meeting

December 1-3, 2015

National Institute Of Aerospace

Hampton, VA



Motivation

- **Question 1: will constellations of opportunity meet the needs of a climate observing system such as CLARREO?**

Factors affecting SI traceability for RO:

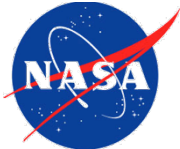
- **Instrument**
- **Environment**
- **Algorithm**

- **Question 2: how do we achieve a climate benchmark?**

- **Instrument design**
- **Analysis**
- **Validation**

➡ CLARREO requirement: 0.03% refractivity accuracy ($\sim 0.06\text{K}$)

➡ RO systematic errors are strongly altitude dependent
(8-20 km altitude is “sweet spot”)



Conclusions

- **Requirements on constellations of opportunity much less stringent than CLARREO requirements**
 - Does not mean we will not meet CLARREO requirements. However, validation techniques need to be developed.
- **Radio occultation is very promising for long-term stability**
 - Encourage more measurements (sampling) w/ caution
- **A call for diversity: diversity in algorithms, implementations, measurement physics, instruments...**
 - Differs from operational requirements
 - Endemic to geophysical science (Mannucci et al., ESS, 2015)
- **The community should strive for at least two, preferably three, independent SI-traceable techniques with sufficient accuracy**

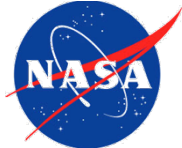


Role of Radio Occultation in Climate Observing Systems

- **Goody et al. paper of 1998 in BAMS (“father of CLARREO”?) identifies hyperspectral IR and RO for testing climate models**

Climate change benchmarks (Wielicki et al., 2013)

- 1. Traceable to fundamental SI standards and robust to gaps in the measurement record;**
 - 2. Time/space/angle sampling sufficient to reduce aliasing bias error in global decadal change observations to well below predicted decadal climate change and below natural climate variability; and**
 - 3. Sufficient information content and accuracy to determine decadal trends in essential climate change variables.**
- **Focus on 1: traceable to SI**
 - **Research continues on 3: information content, synergy with IR**



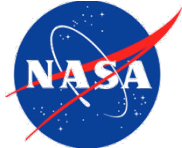
Instrument Designed for Radiometric Accuracy

Key design considerations:

- **Minimal distortion of the incoming signal, independent of signal strength**
- **Time tag precision**
- **Maximize digital processing**

Design choices:

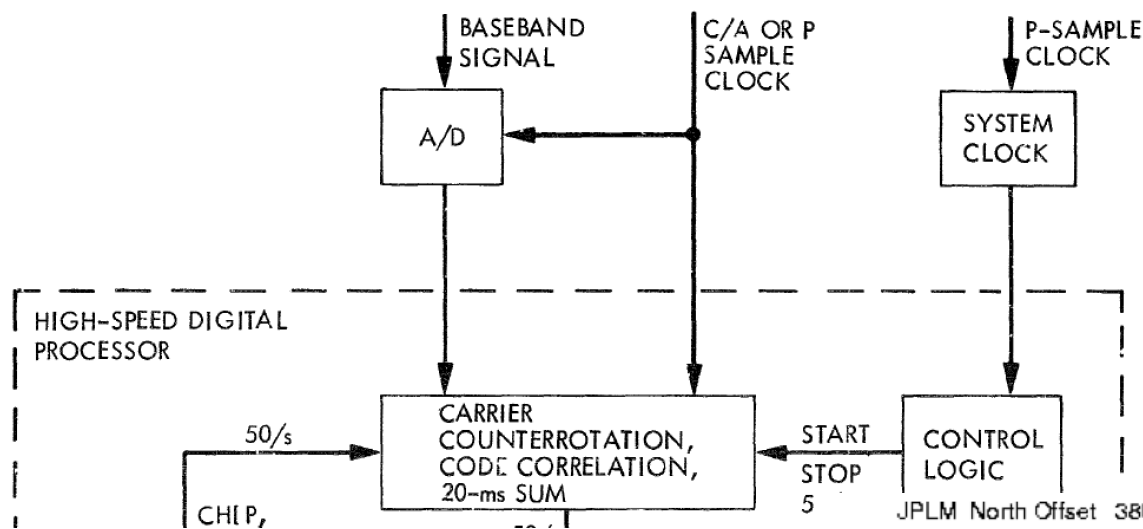
- **Sacrifice SNR for design simplicity: One-bit sampling of input signal, counter-rotation phasors use 3 bits**
- **No multi-level sampling or gain control**
- **Receiver clock time well defined for all operations**



Radiometric Accuracy and Tie to Atomic Clock Standards

Receiver heritage:

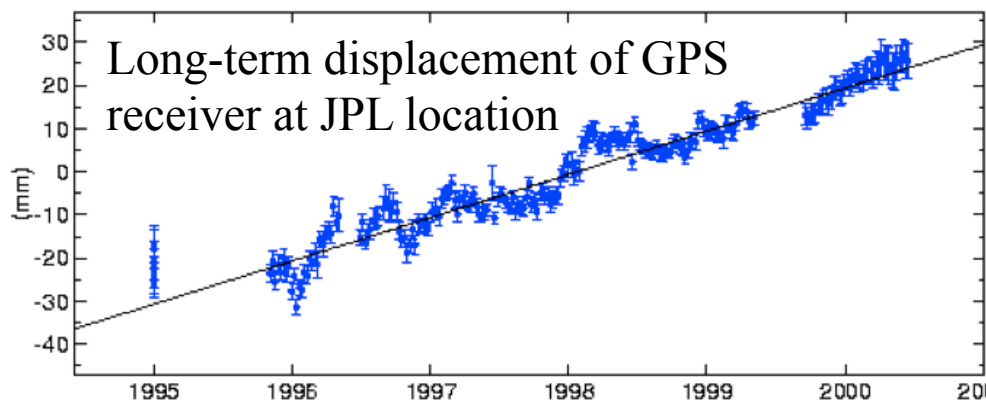
Very Long Baseline Interferometry (VLBI) → “Rogue” → TurboRogue -
→ RO receivers → GRACE instrument (~few micron inter-spacecraft
distance precision at 220 km separation)



“Functional Description of
Signal Processing in the
Rogue GPS Receiver”,
JPL Pub 88-15, 1988.

RO velocity requirements
~0.1 mm/sec

Uses GPS satellite
orbits and clock
estimates



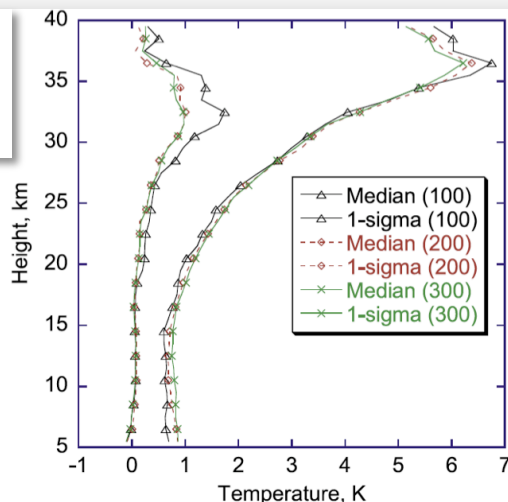


RO Successes

CHAMP vs SAC-C

Observations
Within
1/2 hour
100-300 km

Jul '01-Mar'03
N = 212



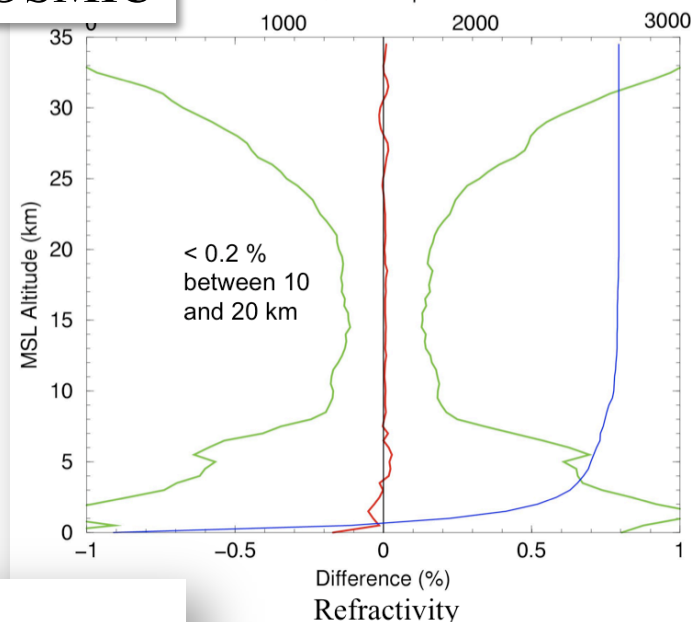
Hajj et al., (2004) "CHAMP and SAC-C
atmospheric occultation results and
intercomparisons", JGR.

Careful accounting for decorrelation with distance

Differences:
Median and
standard
deviation versus
separation

COSMIC

FM3-FM4 (2006.111-300)
Number of pairs



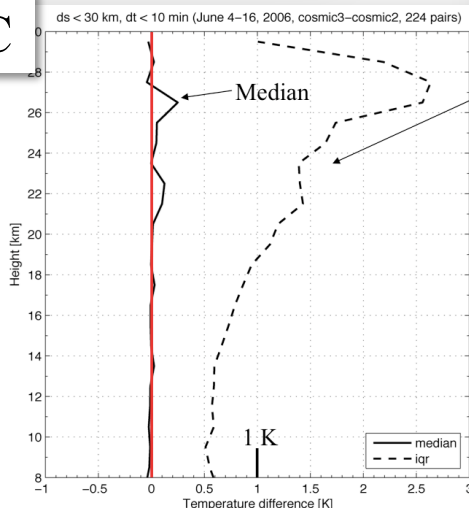
Hajj, G. A., C. O. Ao, B. A. Iijima, D.
Kuang, E. R. Kursinski, A. J.
Mannucci, T. K. Meehan, L. J.
Romans, M. de la Torre
Juarez, and T. P. Yunck (2004),
CHAMP and SAC-C atmospheric
occultation results and
intercomparisons, J. Geophys. Res.,
109, D06109, doi:
10.1029/2003JD003909.

8-30 km

COSMIC

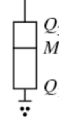
COSMIC3 -
COSMIC2

Window:
30 km
10 minutes
June 4-16, '06
224 pairs



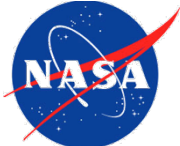
Inter-quartile
Range

Contains
central 50% of
differences



See also:

Schreiner, W., C. Rocken, S.
Sokolovskiy, S. Syndergaard, and D.
Hunt (2007), Estimates of the
precision of GPS radio occultations
from the COSMIC/FORMOSAT-3
mission, Geophys. Res. Lett., 34,
L04808, doi:
10.1029/2006GL027557.



Radio Occultation as a Climate Benchmark

- **Kursinski et al., 1997: “exhaustive” error analysis (36-page JGR paper) was a good start**
- **Covers: Clock error, local multipath, orbit error, residual ionospheric delay, refractivity constants, upper altitude boundary, horizontal structure, water vapor**

Not covered:

- **Smoothing algorithms**
- **Small-scale ionospheric structure (“burst of noise”)**

Covered, but not getting much attention:

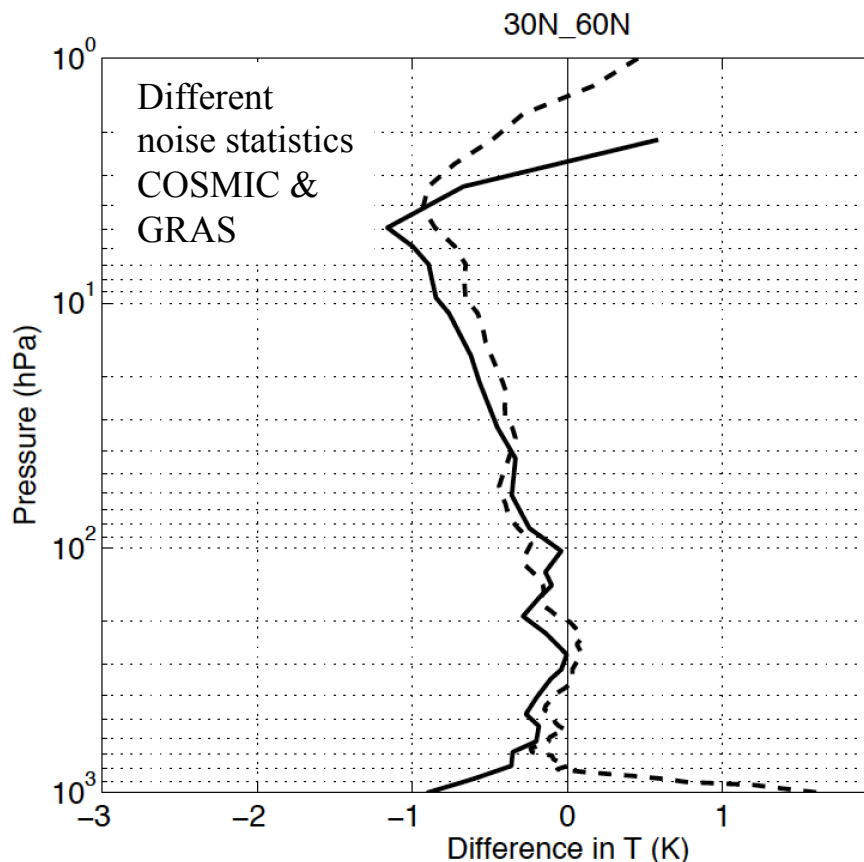
- **Horizontal structure**



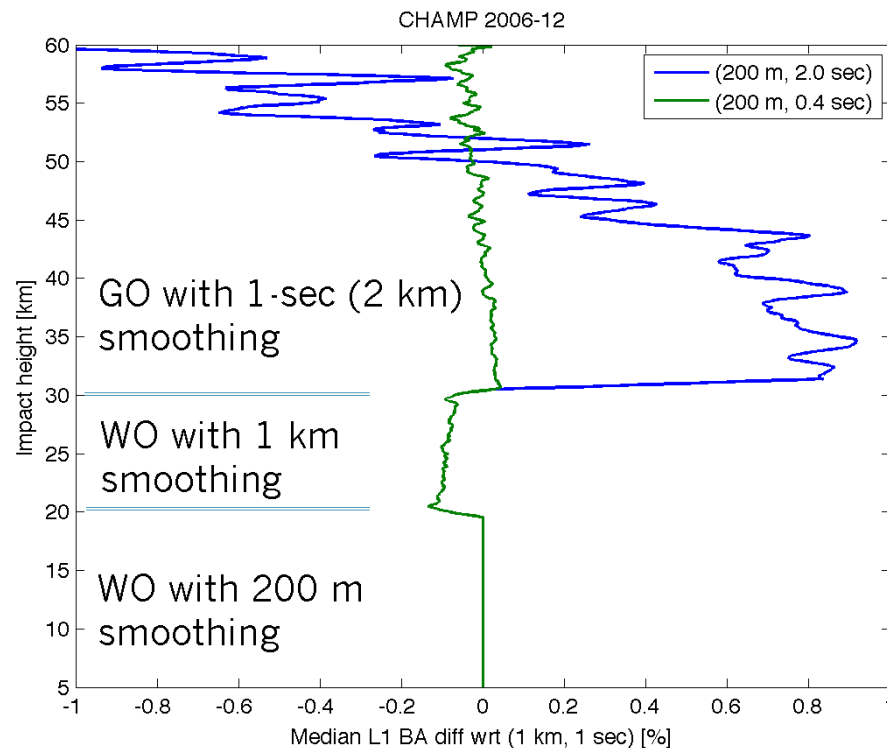
Smoothing Algorithms – Upper Altitudes

K97

(IASI – COSMIC) – (IASI – GRAS)



Median bending angle fractional difference with respect to 1km-1sec smoothed



Chi Ao, JPL

Feltz, M., R. Knuteson, S. Ackerman, and H. Revercomb (2014), Application of GPS radio occultation to the assessment of temperature profile retrievals from microwave and infrared sounders, Atmos. Meas. Tech., 7(11), 3751–3762, doi: 10.5194/amt-7-3751-2014.



Smoothing Algorithms – Lower Altitudes

K97



Improvements to CDAAC Inversion Software: < 8km

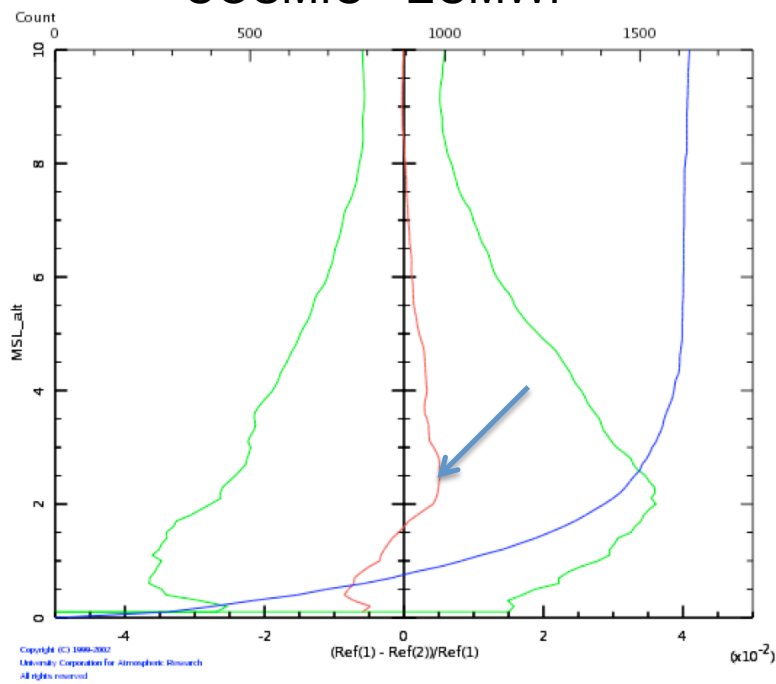


OLD Inversion Software
(With sliding median filter)

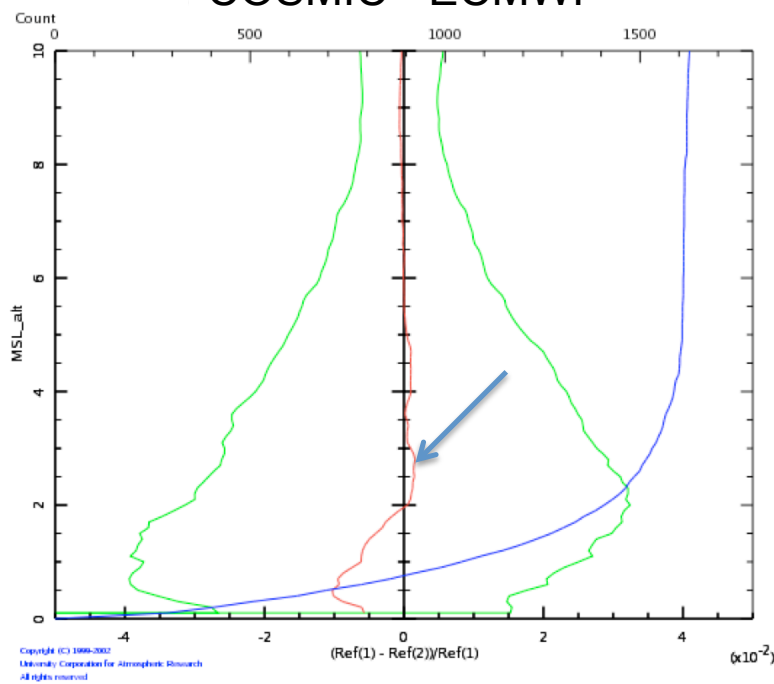
1 July 2007

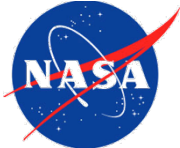
NEW Inversion Software
(Without sliding median filter)

COSMIC - ECMWF



COSMIC - ECMWF

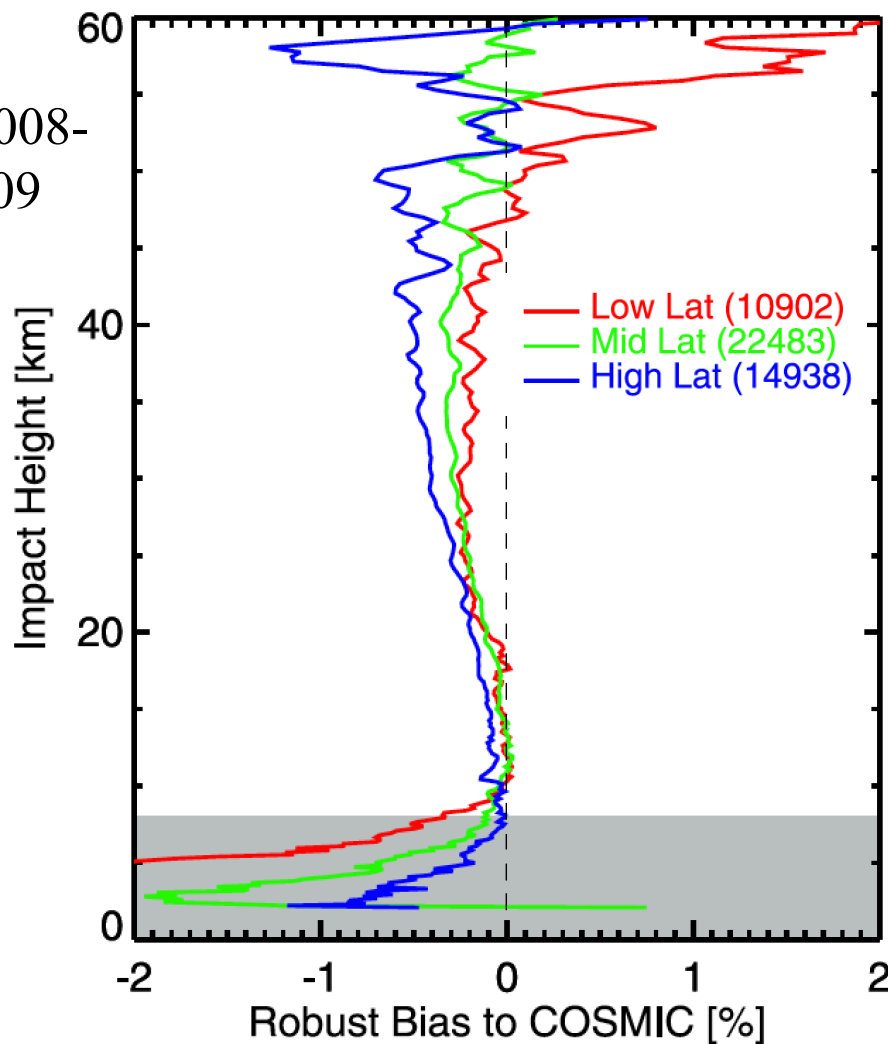




Smoothing Algorithm – Bending Angle

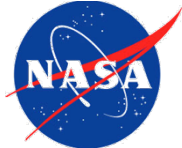
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Bending angle, collocated COSMIC-GRAS



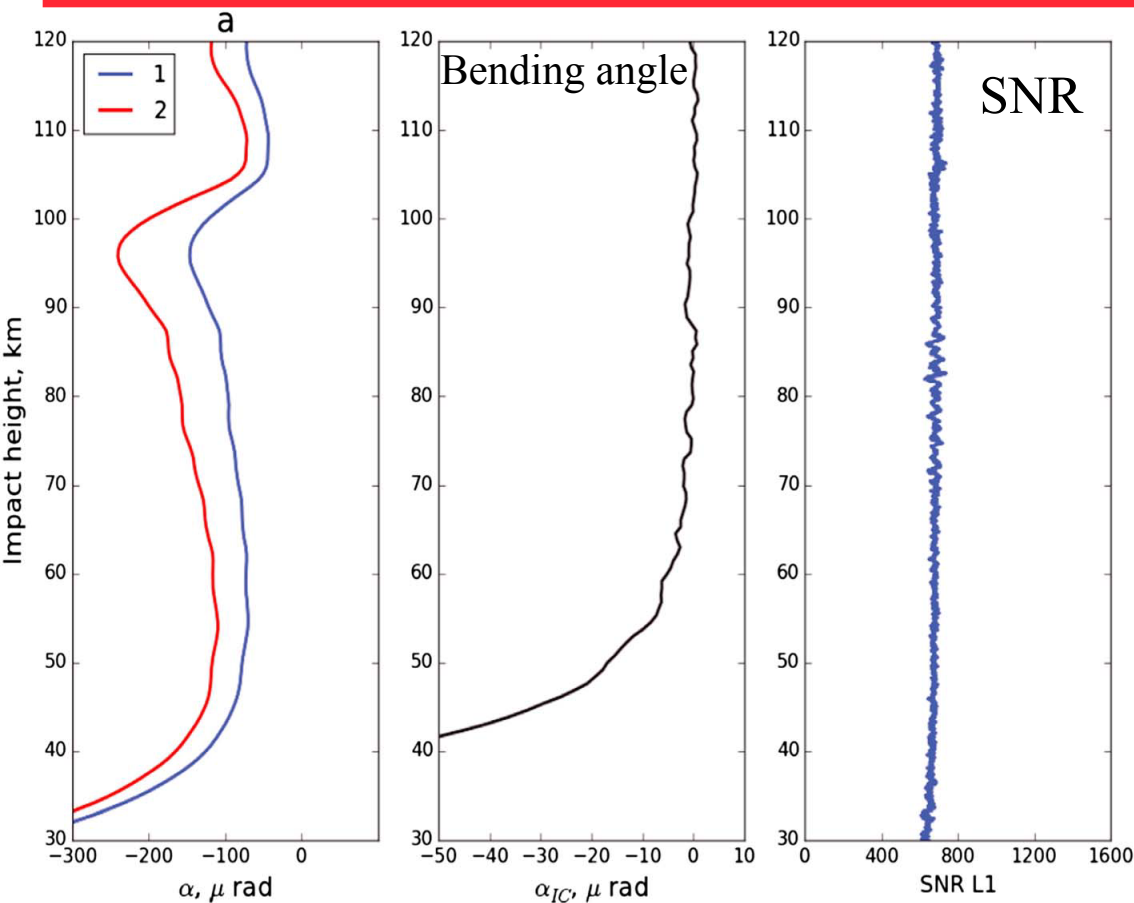
“Further investigations by the GRAS and the COSMIC teams identified the COSMIC phase smoothing as a likely cause. GRAS processing uses a Savitzky-Golay filter while COSMIC uses a Gaussian filter (S. Sokolovskiy, COSMIC team, personal communication, 2009). Processing of COSMIC data at EUMETSAT has shown that the Gaussian filter introduces similar biases. The COSMIC team is currently in the process of updating their operational setup, which should bring the two RO instruments into even better agreement.”

von Engel, A., S. Healy, C. Marquardt, Y. Andres, and F. Sancho (2009), Validation of operational GRAS radio occultation data, *Geophys. Res. Lett.*, 36, L17809, doi:10.1029/2009GL039968.



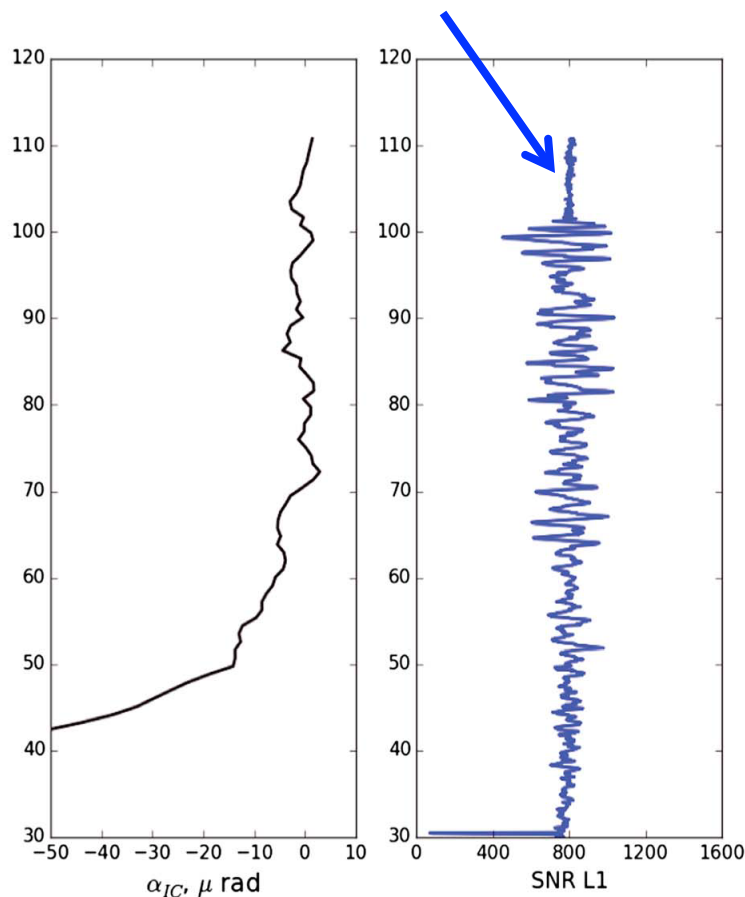
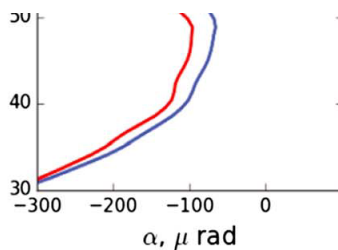
Small-Scale Ionospheric Structure

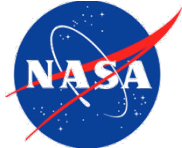
K97



Increased noise due to small-scale ionospheric structures (“scintillation”)

No small scale structure

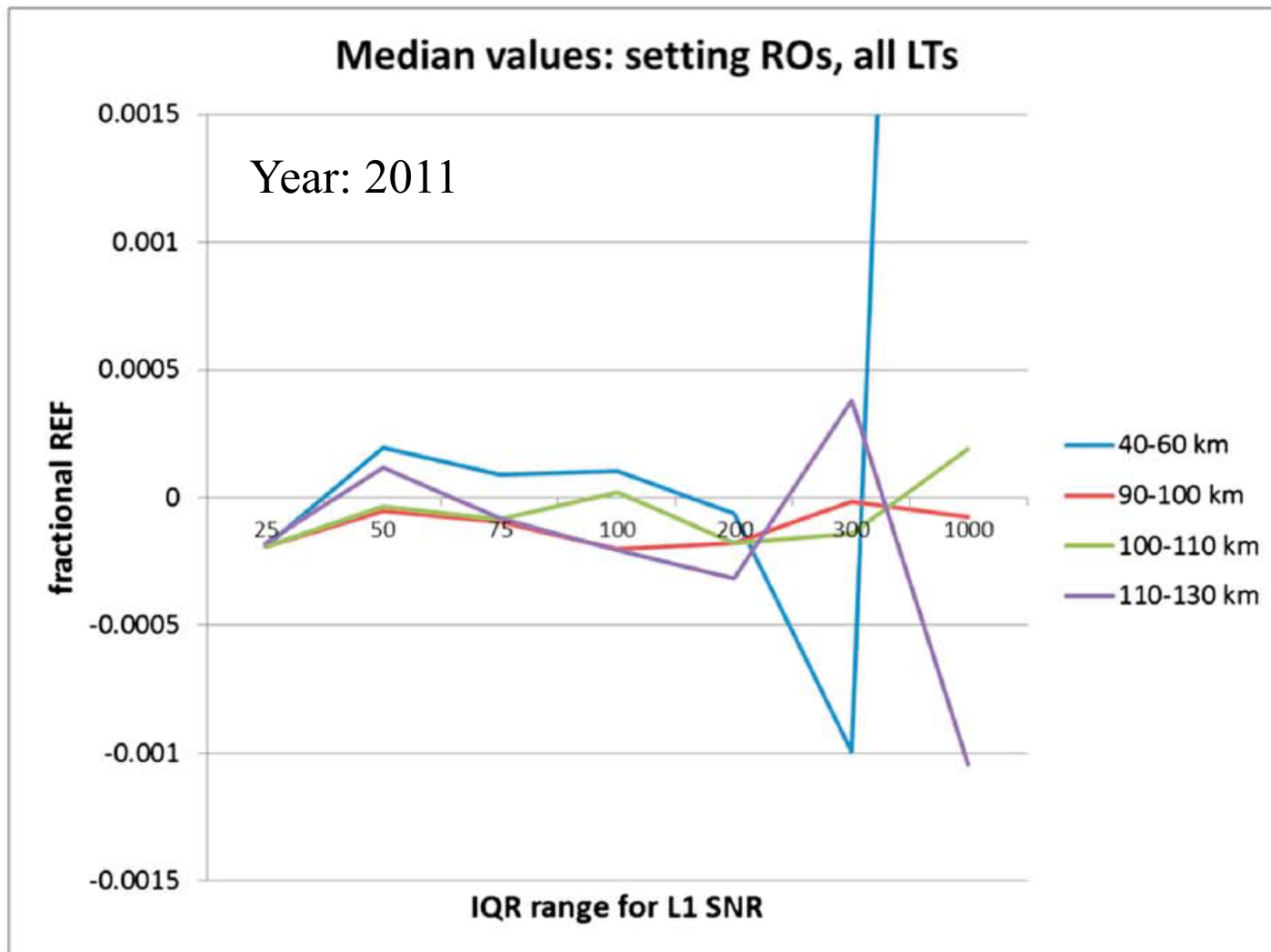




Small-Scale Ionospheric Structure

K97

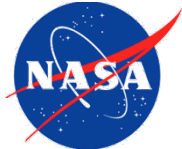
Fractional refractivity difference with ECMWF



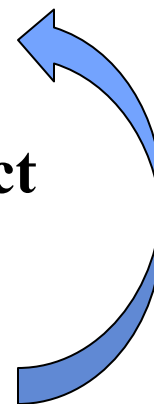
Whereas ECMWF may have a bias, its bias will vary independently of ionospheric small scale structure

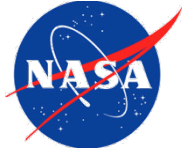
No evidence yet that small scale structure biases the retrievals

Follow-on work: different phases of the solar cycle



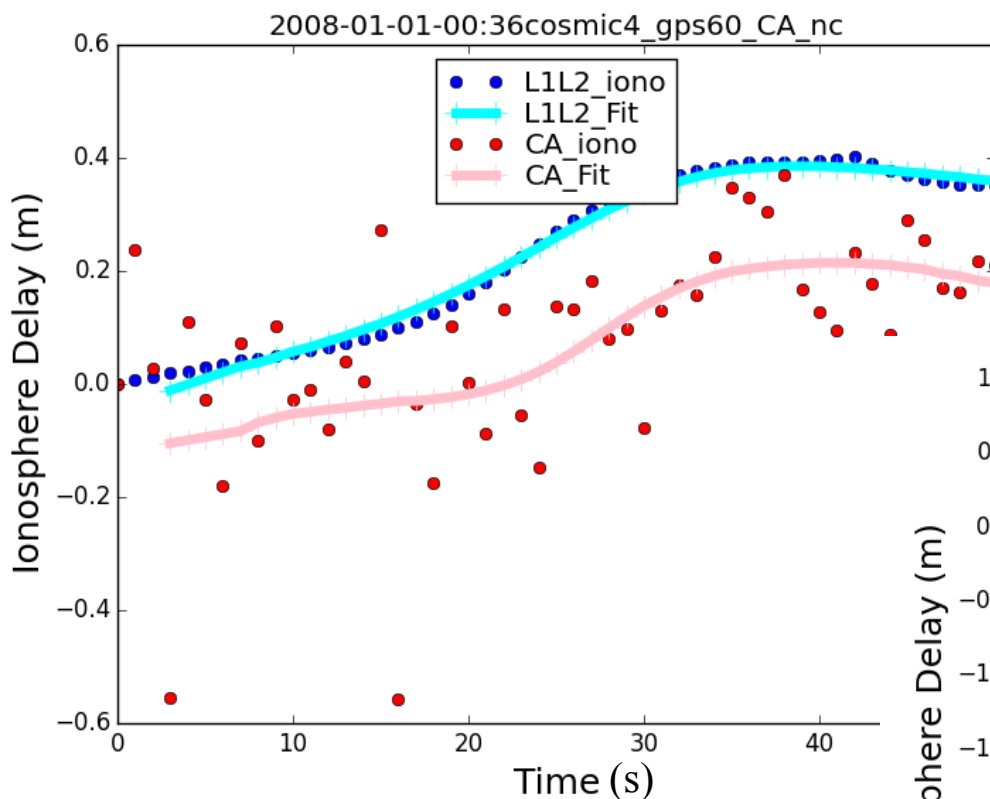
- Investigated in K97
- Residual bias too large above ~20-25 km (CLARREO)
- Stubbornly persistent source of error with a ~11 year variability due to the solar cycle
- Mannucci et al. (OPAC 2010) suggested that spherical asymmetry will limit ability to reduce this error
- Mannucci et al. (Radio Science, 2011) showed that impact varies with orbit altitude
- Healy et al. (2015) developed an appealing method for reducing the impact of this error, however...
- JPL is developing a single-frequency technique to remove first-order impact. Value is in having an alternative method



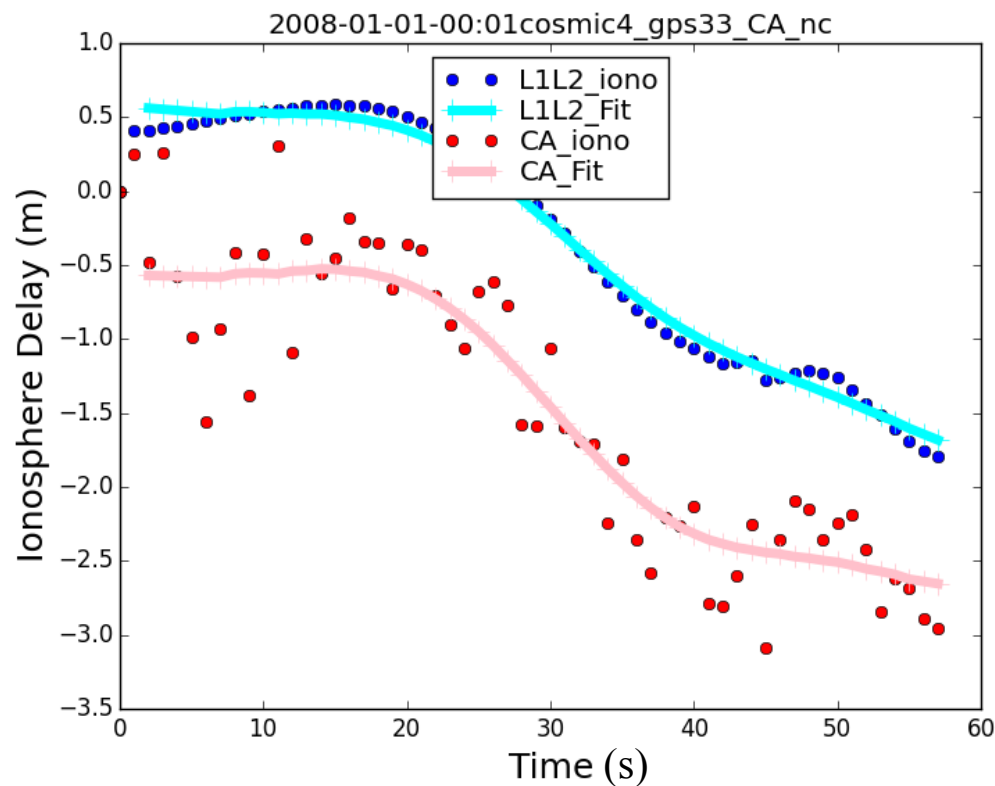


Large-scale Ionospheric Structure

K97



Alternative approach to removing ionospheric effect



- Two examples from 2008
- CA is pseudorange



Refractivity Constants: Increased Accuracy Needed to Meet CLARREO Requirements

K97

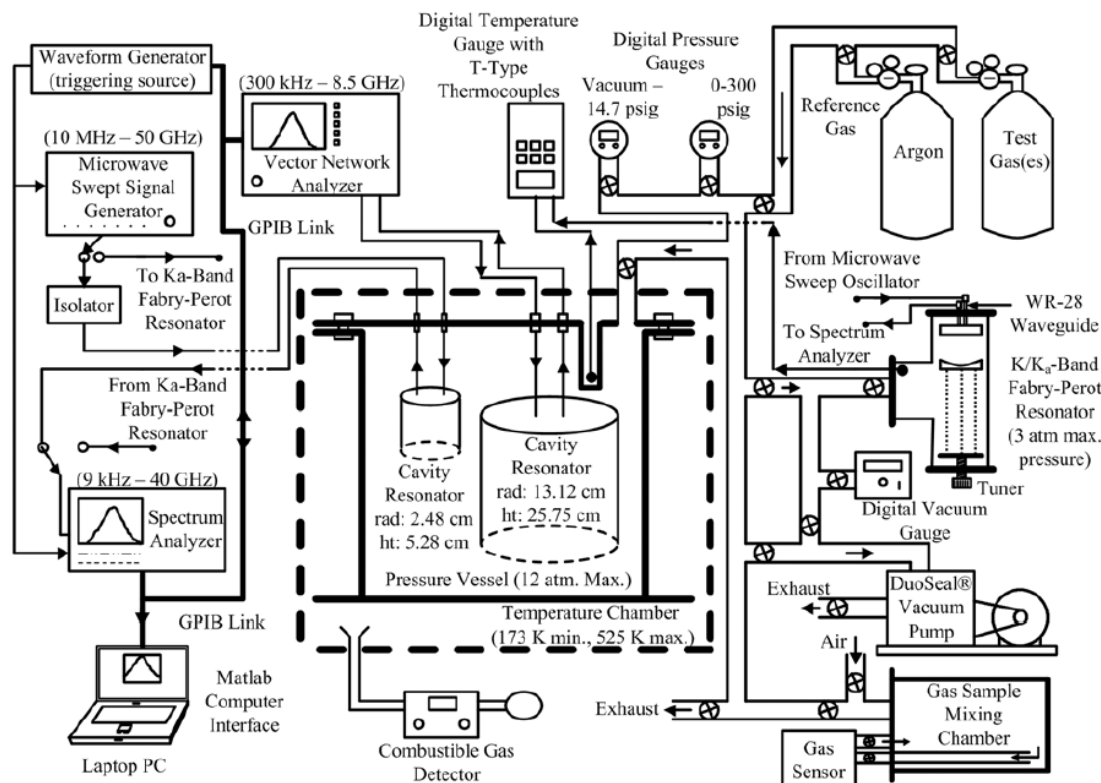
Collect refractivity data at range
of atmospheric conditions $N_r(p_d, p_w, T, CO_2)$

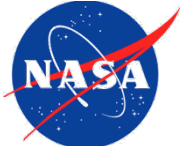
$$N = a_1 \frac{P}{T} + a_2 \frac{P_W}{T^2}$$

Update RO refractivity model based on
precision measurements.

The index of refraction, N_r , which depends on the dry air pressure, p_d , water pressure, p_w , and temperature, T
The CO_2 dependence is one of the major thrusts of this work,

JPL lead:
Brian Drouin





Validation and Assessment Methods

Bias sources for RO: instrument, environment, algorithm

- **Compare to ground truth**
- **Compare to independent estimates with different bias dependencies (e.g. reanalysis)**
- **Compare retrievals that use different algorithms**
 - **Inter-center comparisons**
 - **Vary algorithms at a single center and assess**
- **Compare to independent SI traceable measurements**
- **Compare different instrument designs**
 - **COSMIC (IGOR), MetOp (GRAS), CMA (GNOS)**



GRUAN-GSICS-GNSSRO WIGOS Workshop on Upper-Air Observing System Integration and Application

- **May 6-8 2014 in Geneva at WMO headquarters**
- **Compare methods of estimating measurement uncertainty (including systematic errors), calibration/validation and collocation**
- **Collocation criteria defined:**
 - **IR sounder and GRUAN ~60-90 minutes, 25-50 km**
 - **GNSS-RO and GRUAN ~ 3 hours, 250 km**
- **Each collocated data set will be translated to the other's native "measurement": radiance, bending angle, temperature**
- **Comparisons between observations that use different measurement physics is "climate gold"**
- **WMO Integrated Global Observing System (WIGOS)**



RO-CLIM (under SCOPE-CM, WMO) “Structural Uncertainty” Assessment

Assessment of differences: trends

- Lowest in **tropics & mid-latitude UTLS** (50°S to 50°N and 8 km to 25 km)

Uncertainty in trends per 7 years:

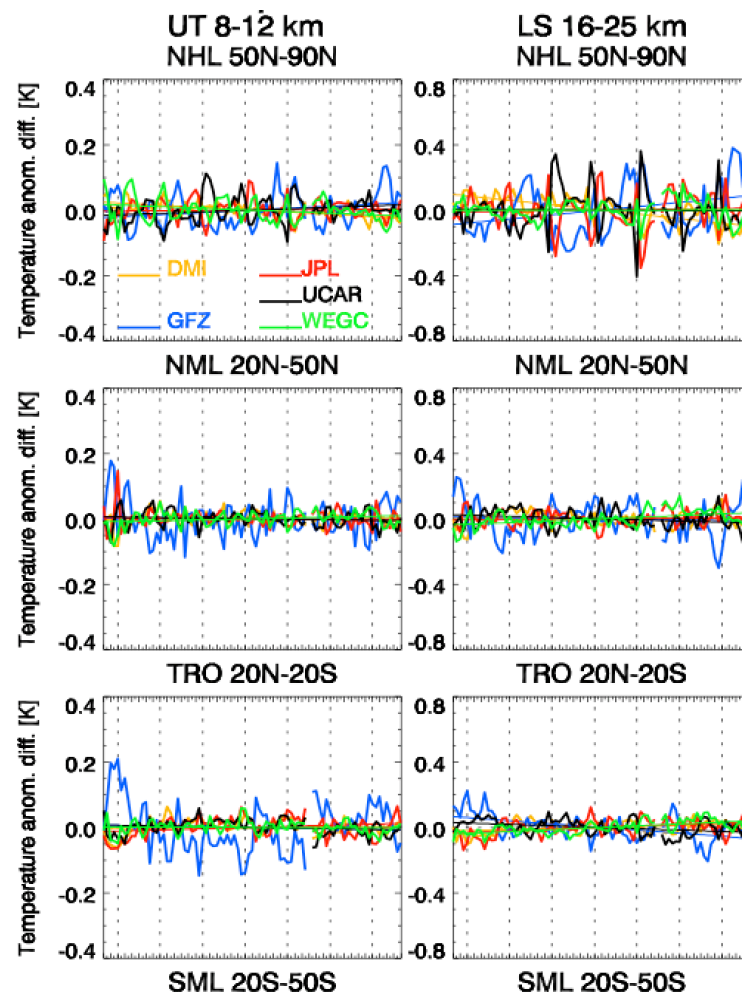
- ~0.02% bending angle, refractivity
- ~0.03% for pressure
- ~2.5 m for geopotential height
- ~0.05 K for temperature
- ✓ Fulfills GCOS requirements for trends
- Being extended to include multi-satellite comparisons

NOTE:

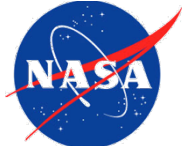
- Absolute differences are larger ~ 0.3K in similar conditions

[Ho et al. *JGR* 2009, 2012; Steiner et al. *ACP* 2013]

CHAMP satellite



Time: 2001-2008 Monthly



An Approach to Bounding Measurement Bias

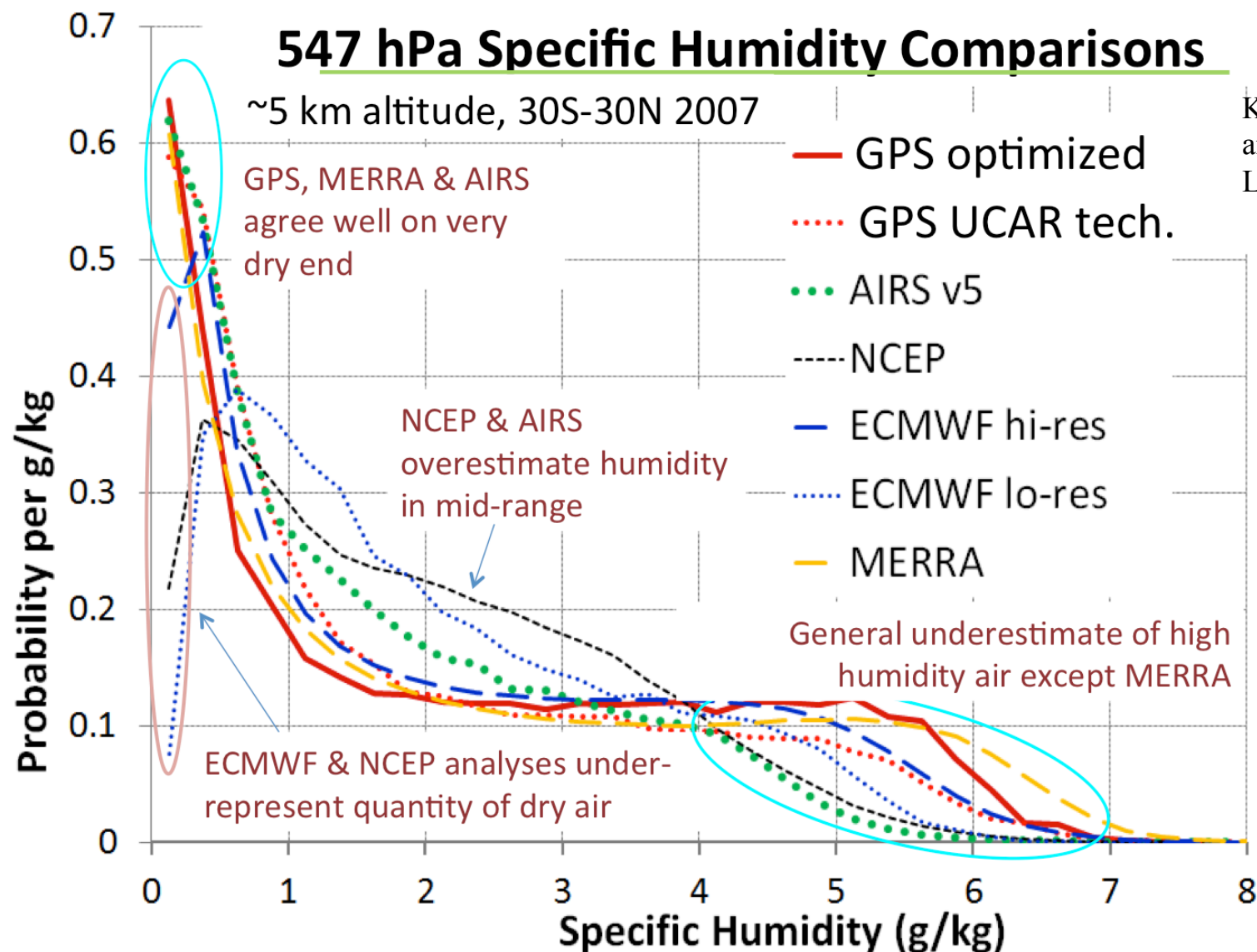
- Addresses “unknown” environmental impact on the retrieval
 - Ionosphere, multipath,...
- Perform two retrievals, that are sensitive in different ways to the (unknown) environment
 - Ionosphere example: dual-frequency versus single-frequency or Healy et al. methods
- For a given environmental condition, calculate the difference between the two retrievals
- An upper bound can be set on the bias error caused by the environment

$$R_1 = \tau + \epsilon_1$$

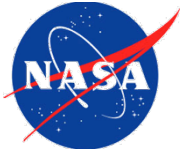
$$R_2 = \tau + \epsilon_2 \quad \frac{\epsilon_2}{\epsilon_1} < g \text{ is calculable based on theory} \Rightarrow \epsilon_1 < \frac{R_1 - R_2}{g - 1}$$



RO-IR Synergy

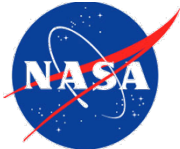


Kursinski, Earth
and Space Science
LLC



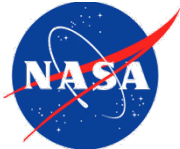
NASA MEASURES

- **“A Multi-Sensor Water Vapor, Temperature and Cloud Climate Data Record”, Eric Fetzer, JPL is PI**
- **Results: water vapor with GPS versus water vapor with AIRS, classified by cloud type**

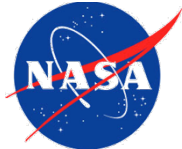


Conclusions

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 - Does not mean we will not meet CLARREO requirements. However, validation techniques need to be developed.
- **Radio occultation is very promising for long-term stability**
 - Encourage more measurements (sampling) w/ caution
- **A call for diversity: diversity in algorithms, implementations, measurement physics, instruments...**
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BACKUP SLIDES

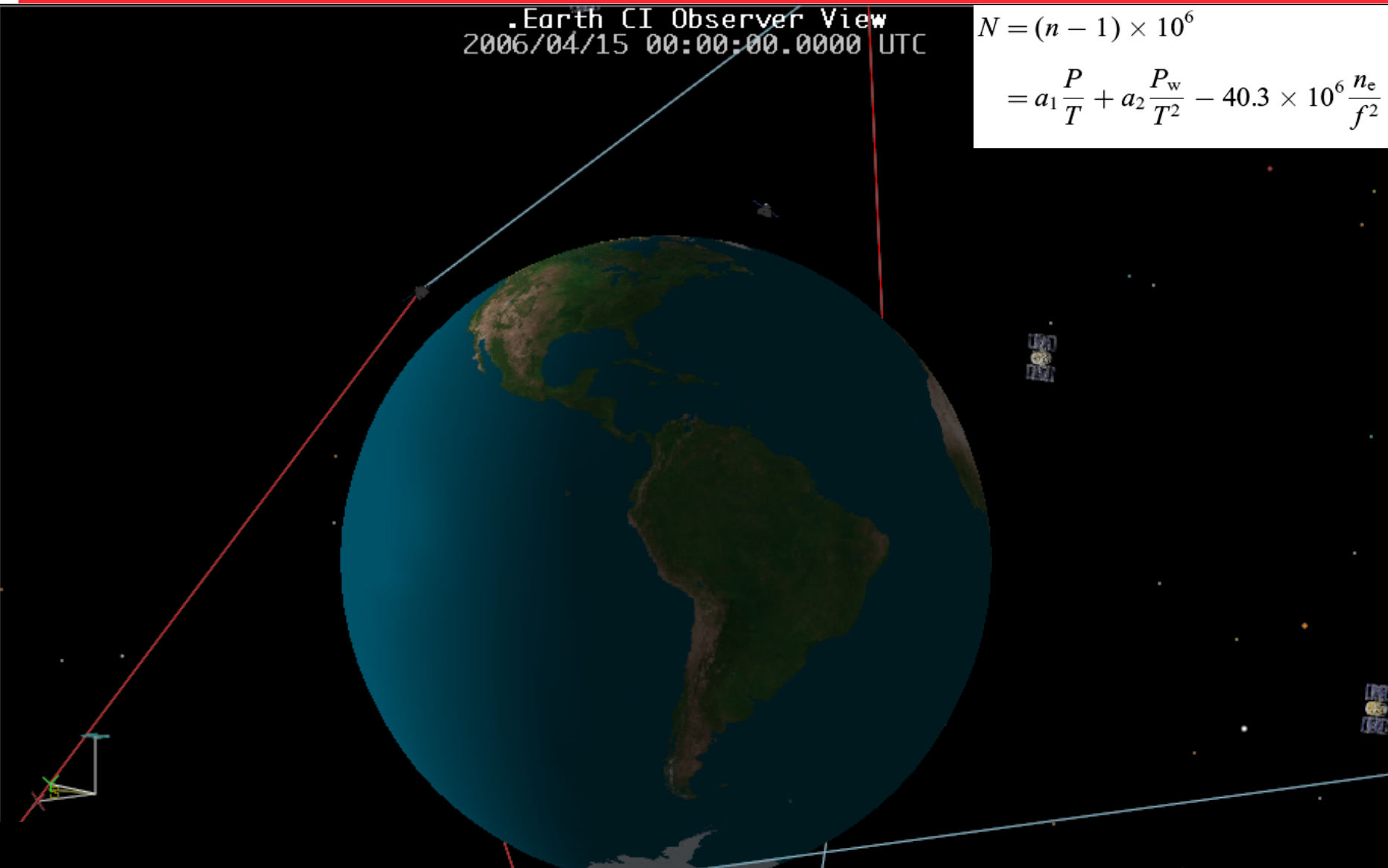


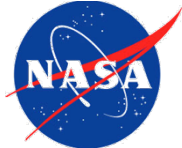
Radio Occultation

.Earth CI Observer View
2006/04/15 00:00:00.0000 UTC

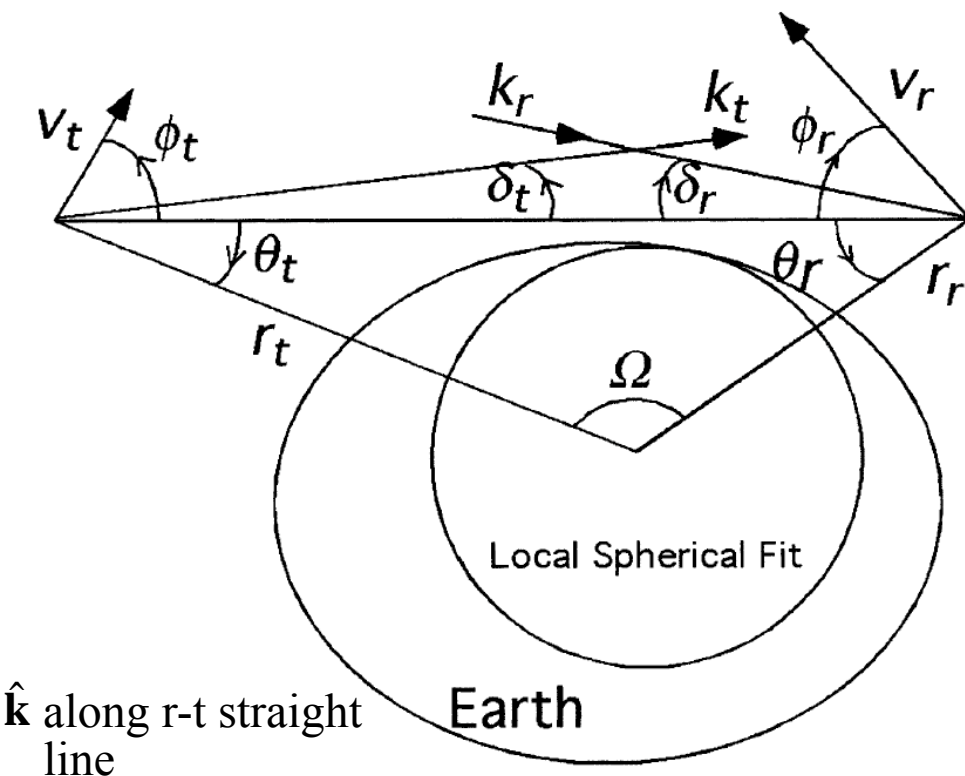
$$N = (n - 1) \times 10^6$$

$$= a_1 \frac{P}{T} + a_2 \frac{P_w}{T^2} - 40.3 \times 10^6 \frac{n_e}{f^2}$$





GPS: Bending Angle to Doppler Shift



Rate of change of atmospheric delay:

$$\frac{d\gamma}{dt} = \lambda \Delta f = [\mathbf{v}_t \cdot \hat{\mathbf{k}}_t - \mathbf{v}_r \cdot \hat{\mathbf{k}}_r - (\mathbf{v}_t - \mathbf{v}_r) \cdot \hat{\mathbf{k}}]$$

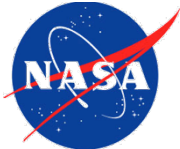
Assuming spherical symmetry:

$$\begin{aligned} \frac{d\gamma}{dt} = & (v_t \cos(\phi_t - \delta_t) - v_r \cos(\phi_r - \delta_r)) \\ & - (v_t \cos \phi_t - v_r \cos \phi_r) \end{aligned}$$

$$a = r_t n_t \sin(\theta_t + \delta_t) = r_r n_r \sin(\theta_r + \delta_r)$$

Doppler shift: Δf

- Time is clearly the fundamental measurement in a radio occultation, leading to accurate measurements of Doppler shift
- Orbits must be known to high accuracy also ($\sim \text{cm}$, $< 0.1 \text{ mm/sec}$)



Requirements Meeting

- **A meeting was held at JPL on February 2, 2010 to discuss the CLARREO RO requirements document**
 - JPL, Harvard (Leroy), U. Arizona (Kursinski), UCAR, CLARREO project (Young and Corliss, Wielicki)
- **Identify the error sources (13) that deserve more scrutiny, and possible new requirements (23) levied on the observatory, processing system, receiver, etc.**

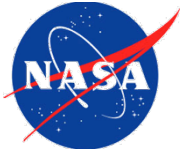


Stephen Leroy

Requirements partitioning (18km)

$$\underbrace{\sigma_{\text{error}}^2 \left(\frac{1 \text{ yr}}{\tau_{\text{mission}}} \right)}_{0.03\%} = \underbrace{\sigma_{\text{systematic}}^2}_{0.017\%} + \underbrace{\sigma_{1\text{-yr random}}^2 \left(\frac{1 \text{ yr}}{\tau_{\text{mission}}} \right)}_{0.025\%}$$

Fractional refractivity error



Refractivity Requirements

- There is no clear proof that current GPS RO measurements satisfy CLARREO mean refractivity requirement of 0.03%.
- However, increased SNR and reduced multipath from the instrument along with improved processing to reduce errors due to ionospheric residuals and Abel upper boundary conditions should ensure that the CLARREO requirements can be met.



Survey of Existing Estimates (5-20 km)

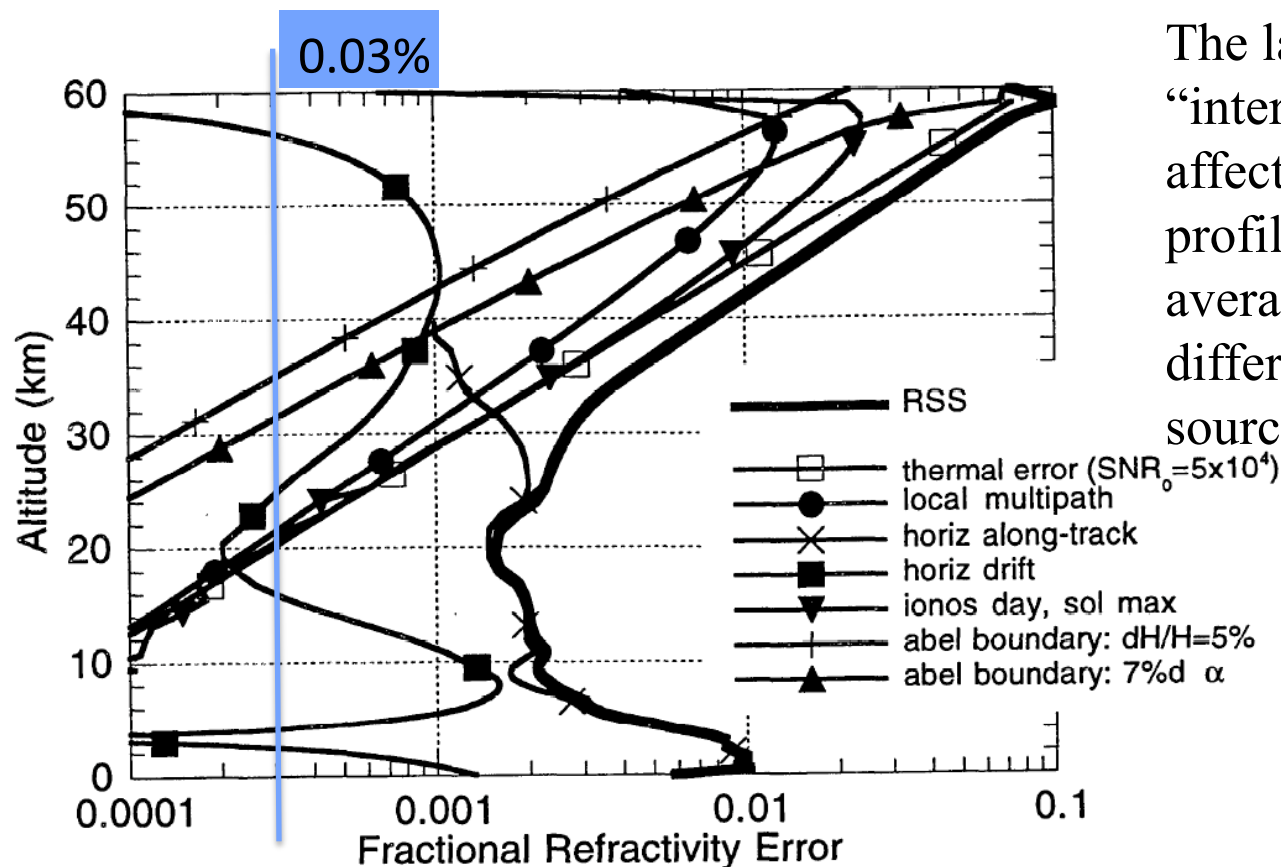
Theoretical	Comparison with Others (Measurements and Analyses)	Comparison with Self (Precision, Sensitivity tests)
End-to-end calculations (RMS ~ 0.2% from Kursinski et al., 1997)	Radiosondes (Mean ~ 0.2 %, RMS ~ 1.5 % in refractivity from Kuo et al., 2005)	CHAMP-SACC, COSMIC-COSMIC pair analysis (RMS ~ 0.2%-0.4% in refractivity from Schreiner et al., 2007 and Hajj et al., 2004)
	Satellite measurements: AIRS, MLS, MSU, etc. (RMS ~ 1.5 K from various pubs; implies ~ 1% in refractivity)	Comparison among different processing centers (Zonal means ~ 0.1% in refractivity from Ho et al., 2010)
	ECMWF/NCEP (RMS ~ 1% in refractivity from various pubs)	

Chi Ao, JPL



Theoretical Estimates

KURSINSKI ET AL.: OBSERVING EARTH'S ATMOSPHERE BY OCCULTATION USING GPS



The largest errors are “interpretive” affecting individual profiles. Climate averages provide different error sources.

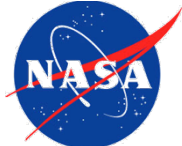
1997

Figure 10. Summary of refractivity errors versus height. Thermal error, 1 s $\text{SNR} = 5 \times 10^4$; local multipath, 10 mm rms spread over 0.01 Hz; horizontal refractivity structure, along track from simulation and horizontal motion of ray path tangent point from tropospheric and stratospheric climatologies near 30°S for June-July-August; ionosphere error, daytime, solar maximum conditions; Abel boundary errors, 7% in α , 5% in H_α .



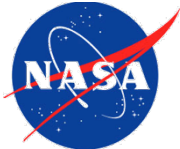
Errors Requiring Further Analysis (Sample)

Category	Component	Description	Comments/Mitigation
ERROR E.1	Systematic	“Worst-case” <i>correlations among systematic biases</i> must be taken into account, for example, between missions or interannual error correlation. Biases may be correlated within their error bars. How does that affect the time-to-detect analysis?	Requires additional analysis, including plausible error sources that create correlations.
ERROR E.9	Mission	<i>Sampling error for the threshold mission of one satellite</i> may exceed requirements. Opinions differed on adequacy of existing analysis to handle the one-satellite case, and whether one satellite is sufficient.	
ERROR E.10	Systematic	<i>Horizontal grazing error could create biased climate averages.</i> Grazing occultations across semi-stationary features of the atmosphere might cause errors that change slowly (inter-annually).	Will rising and setting occultations help to compensate this error in climate averages?
ERROR E.13	Systematic	<i>The contribution of liquid water to the refractivity will be known to within (TBD refractivity units) for each occultation.</i>	Liquid water contribution must be bounded.



Additional Requirements (Sample)

Category	Component	Description	Comments/Mitigation
REQMNT R.4	Observatory	<i>Survey center of mass of the observatory.</i> Corliss wants to know how accurately center of mass needs to be surveyed throughout the mission duration. Issues: propellant, vertical and horizontal components, articulating solar array.	
REQMNT R.5	Observatory	<i>The observatory shall carry a USO</i> (10^{-13} over 1 second) to permit multiple paths to SI traceability to be carried out.	
REQMNT R.10	Processing and Instrument	<i>The processing system will use three frequencies to mitigate ionospheric error and the instrument will track three GNSS frequencies.</i>	Correction to $<5 \times 10^{-8}$ rad is achievable. We lack consensus on this requirement.
REQMNT R.21	Instrument	The <i>occultation scheduling algorithm on the instrument</i> shall not increase the sampling bias more than (TBD)% relative to the simulation studies used to determine the sampling bias.	We need to make sure that the occultation scheduler provides suitable occultation distributions.
REQMNT R.23	Observatory	The observatory shall carry satellite laser ranging mirrors to provide multiple independent pathways to determining orbit error.	This needs further review.



Summary (2010)

- **Extensive review of requirements and potential error sources has occurred**
 - By no means complete
- **Discussions have been held with the project on implications for the antenna**
- **New technology that can aid SI-traceability has been identified**
- **The TriG receiver is under development now**
- **COSMIC-Follow-On is an encouraging development that might benefit CLARREO**